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Elliptical Galaxies with Emission Lines from the Sloan Digital Sky Survey

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Abstract We present the results of 11 elliptical galaxies with strong nebular emission lines during our study of star formation history along the Hubble sequence. After removing the dilution from the underlying old stellar populations by use of stellar population synthesis model, we derive the accurate fluxes of all emission lines for these objects, which are later classified with emission line ratios into one Seyfert 2, six LINERs and four HII galaxies. We also identify one HII galaxy (A1216+04) as a hitherto unknown Wolf-Rayet galaxy from the presence of the Wolf-Rayet broad bump at 4650 Å. We propose that the star-forming activities in elliptical galaxies are triggered by either galaxy-galaxy interaction or the merging of a small satellite/a massive star cluster, as already suggested by recent numerical simulations.

Key words: Galaxies: elliptical and lenticular, cD – Galaxies: starburst – Galaxies: individual: A1212+06, A1216+04, CGCG13-83, IC 225

1 INTRODUCTION

The star formation history of elliptical galaxies carries an important information for their formation and evolution and has invaluable constraints for the cosmological models (Eggen, Lynden-Bell & Sandage 1962). In the conventional view, an elliptical galaxy was thought to be a simple stellar system with old stellar population formed in a single star forming activity at very early stage of the galaxy forming history, quiescent and passively evolving ever since, and very few new stars are made in the past 1− 2 Gyrs

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(Searle, Sargent & Bagnuolo 1973; Larson 1975). However, in recent decades a rival view has been proposed based on the hierarchical clustering models (White & Rees 1978; Kauffmann, White & Guiderdoni 1993), which requires that the most massive objects form at late time via merging smaller subunits. In this scenario, massive ellipticals are formed through merging of two spiral galaxies, as have also been shown by numerical simulations (see the recent review by de Freitas Pacheco, Michard & Mohayaee 2003; Toomre & Toomre 1972; Barnes 1992; Barnes & Hernquist 1992; Bendo & Barnes 2000).

Recently Fukugita et al. (2004) have reported the discovery of active star-forming activities in the field elliptical galaxies from the Sloan Digital Sky Survey (SDSS). They found that the percentage of such star-forming elliptical galaxies is a few tenths of a percent in their sample and suggested that these star-forming ellipticals could be the progenitors of E+A galaxies, which are devoid of nebular emission lines but with very strong Balmer absorption lines superimposed with an old stellar population, and are interpreted as being the post-starburst ended within the last $1.5 - 2$ Gyr (Couch & Shaples 1987; Barger et al. 1996). In this paper, we will present more examples of such star-forming elliptical galaxies which show the unambiguous evidence of young star-forming activities during our study of star formation history along the Hubble sequence.

This paper is organized as follows: we give the sample of 11 ellipticals with strong emission lines in Section 2. In Section 3, we present the results of stellar population synthesis, use the standard BPT diagrams to classify the ionizing mechanism for these 11 ellipticals, and study radial profiles, color distribution and star forming activities for three HII galaxies (A1212+06, A1216+04 and CGCG13-83). Finally we discuss in Section 4 and present our conclusions in Section 5. Where appropriate we adopt a Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2 THE DATA

The Sloan Digital Sky Survey (SDSS) is the most ambitious astronomical (both photometric and spectroscopic) survey project which has ever been undertaken (Gunn et al. 1998; Blanton et al. 2003).

Recently, we cross-correlate the SDSS DR2 spectroscopic archive dataset with the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1991) by positional match with accuracy of $\sim$ 10 arcsec, and derive a sample of 1027 galaxies with both morphological classification and spectroscopic information, among of which 48 sources are cataloged as Elliptical galaxies in RC3 with mean numerical index (T) of either -4 or -5. Our main target is to study the star formation activity along the Hubble sequence, which will be presented by Shi et al. (2005).

In this paper we show that among these 48 elliptical galaxies, 11 objects clearly present strong nebular emission lines with Hα equivalent width (EW) larger than 2Å,

which are not classified as AGNs before either in the catalog of *Quasars and Active Galactic Nuclei* (Veron-Cetty & Veron 2003, 11th Ed.) or in any literature. The basic properties of these 11 ellipticals are summarized in Table 1, where we give the galaxy name, coordinate, redshift, distance, absolute blue magnitude and morphological type, respectively.

Table 1 Parameters of 11 elliptical galaxies with emission lines from SDSS

Name	RA (2000)	DEC (2000)	Redshift	Distance (Mpc)	M_B	Morphology
NGC 426	01h12m48.6s	-00d17m24.6s	0.0173	69.2	-20.4	E+
NGC 677	01h49m14.0s	+13d03m19.1s	0.0170	68.0	-21.0	E0
IC 225	02h26m28.2s	+01d09m37.9s	0.0051	20.4	-17.1	E0
CGCG 13-83	12h08m23.5s	+00d06m36.9s	0.0408	163.2	-21.2	E0
NGC4187	12h13m29.2s	+50d44m29.3s	0.0305	122.0	-21.4	E0
A1212+06	12h15m18.3s	+05d45m39.4s	0.0067	26.8	-17.3	E0
A1216+04	12h19m09.8s	+03d51m23.3s	0.0051	20.4	-17.1	E0
NGC4581	12h38m05.1s	+01d28m39.9s	0.0062	24.8	-18.8	E+
NGC5216	13h32m06.9s	+62d42m02.4s	0.0979	39.2	-19.5	E0
IC 989	14h14m51.3s	+03d07m51.3s	0.0253	101.2	-21.3	E0
NGC5846	15h06m29.1s	+01d36m20.9s	0.0057	22.8	-20.9	E0

3 RESULTS

During the study of emission-line spectra, an unavoidable issue is the contamination from the underlying old stellar population, especially to the Balmer lines. The standard method is to use the stellar population synthesis model to fit the observed spectrum. In this paper, we use the same stellar population synthesis code, STARLIGHT version 2.0, (Cid Fernandes et al. 2004) to study 11 elliptical galaxies. The routine searches for the linear combination of 45 Simple Stellar Populations (SSP) from the recent stellar population model of Bruzual & Charlot (2003) for 3 metallicities (0.2 $Z_\odot$, $Z_\odot$, and 2.5 $Z_\odot$), for each metallicity we select 15 different age components, ranged as 0.001, 0.003, 0.005, 0.01, 0.025, 0.04, 0.10, 0.29, 0.64, 0.90, 1.4, 2.5, 5.0, 11 and 13 Gyr. The match between model and observed spectrum is evaluated by the ruler of χ square minimum, and the search for the best parameters is carried out with a simulated annealing method, which consists of a series of 10^7 likelihood-guided Metropolis tours through the parameter space (see also Cid Fernandes et al. 2005).

After subtracting the best-fit model from the observed one, we derive the pure emission-line spectrum, from which we could measure the accurate fluxes for all emis-

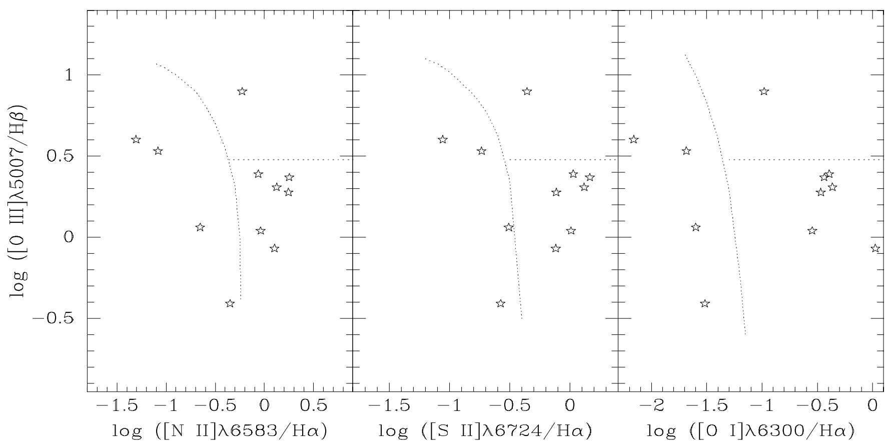

Fig. 1 Diagnostic diagrams. *left.* log([N II]λ6583/Hα) vs. log([O III]λ5007/Hβ); *middle.* log([S II]λ6724/Hα) vs. log([O III]λ5007/Hβ); *right.* log([O I]λ6300/Hα) vs. log([O III]λ5007/Hβ). The dotted lines divided narrow-line AGNs from starburst galaxies are taken from Veilleux & Osterbrock (1987).

sion lines with the IRAF [1] *specfit* or *onedspec.splot* software, the results are presented in Table 2. The line flux errors are typically around 5%. It is well known that we can distinguish narrow-line AGNs from normal star-forming galaxies by using emission line flux ratios, the so-called BPT diagrams (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987). With our measurement of emission lines from the pure emission-line spectra, we classify these 11 ellipticals into three types: one Seyfert 2, six LINERs and four HII galaxies(see Figure 1). We find that three HII galaxies (A1212+06, A1216+04 and IC 225) are in fact dwarf galaxies with absolute B magnitude (M$_B$) smaller than -18, as shown in Table 1.

It will be easy to understand Seyfert and LINER activities in elliptical galaxies, such as the host galaxies of the most powerful AGNs (quasars) are usually the massive elliptical galaxies (Floyd et al. 2004), that is because the recent discovery of a tight relation between bulge velocity dispersion and black hole mass, which strongly suggests that massive black holes are ubiquitous and scale with the bulge masses (Ho & Kormendy 2000; Tremaine et al. 2002). While the pure star-forming activities in elliptical galaxies are especially

[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by Associated of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 2 Emission Lines Properties and Classifications for 11 Elliptical Galaxies

Galaxy				Flux[a]				Type
	Hβ	[O III]λ4959	[O III]λ5007	[O I]λ6300	Hα	[N II]λ6583	[S II]λ6724	
A1212+06	3404.6	3809.3	11607.2	207.1	10013.9	829.0	1846.7	HII
A1216+04	4224.0	5648.2	16918.5	127.8	18514.3	914.1	1628.5	HII
CGCG13-83	239.4	35.4	93.5	31.0	1017.8	454.3	270.2	HII
IC 225	862.6	331.5	994.6	90.2	3262.3	720.9	1008.4	HII
IC 989	171.4	97.9	349.0	302.5	698.8	931.6	914.1	LINER
NGC4187	246.6	176.2	576.9	351.7	963.0	1720.0	1404.7	LINER
NGC 426	579.9	297.4	1099.2	910.8	2681.4	4708.7	2056.7	LINER
NGC4581	909.0	2354.2	7203.8	405.8	3893.6	2310.0	1711.5	Seyfert
NGC5216	124.7	67.3	306.0	238.3	588.7	509.8	626.3	LINER
NGC5846	302.8	160.6	258.4	695.8	658.6	833.2	501.3	LINER
NGC 677	263.1	71.8	288.4	303.3	1069.2	979.5	1088.7	LINER

[a] fluxes are in units of 10^{-17} erg s^{-1} cm^{-2}

rare, the nature and triggering mechanism are still open questions. In the following part of this paper, we will concentrate on the detailed study of three star-forming galaxies (A1212+06, A1216+04 and CGCG 13-83). For the fourth one (IC 225), Gu et al. (2005) discovered it is a compact dwarf elliptical galaxy with a peculiar blue core which contains two distinct nuclei, separated by 1.4 arcseconds. The off-nucleated core could be a dwarf galaxy or a halo cluster, swallowed by IC 225 and thus triggered the starburst activity in IC 225.

In Figure 2, we show the false-color RGB images for 4 star-forming elliptical galaxies, which combine information from g-, r- and i-band SDSS images by using the algorithm given by Lupton et al. (2004). In Figure 3, we plot their SDSS optical spectra, where the insets in three panels (a, c, d) are the enlarged views of the higher-order Balmer absorption lines in the wavelength of 3750 – 4150 Å. The inset in panel (b) shows enlargement on the Wolf-Rayet blue bump around 4650 Å.

3.1 Radial Surface Brightness Distribution

The typical radial surface brightness distribution for ordinary elliptical galaxies is the de Vaucouleurs $R^{1/4}$ law (de Vaucouleurs 1953). Since the SDSS photometrical survey at u- and z-bands are much shallower(Fukugita et al. 1996) and i-band used a thinned CCD, an instrumental effect known as the "red halo" in the PSF wings are reported to seriously affected the i-band photometric analysis (e.g., Wu et al. 2005). We will only derive g- and r-band stellar surface brightness distributions by using the standard task *ellipse* in

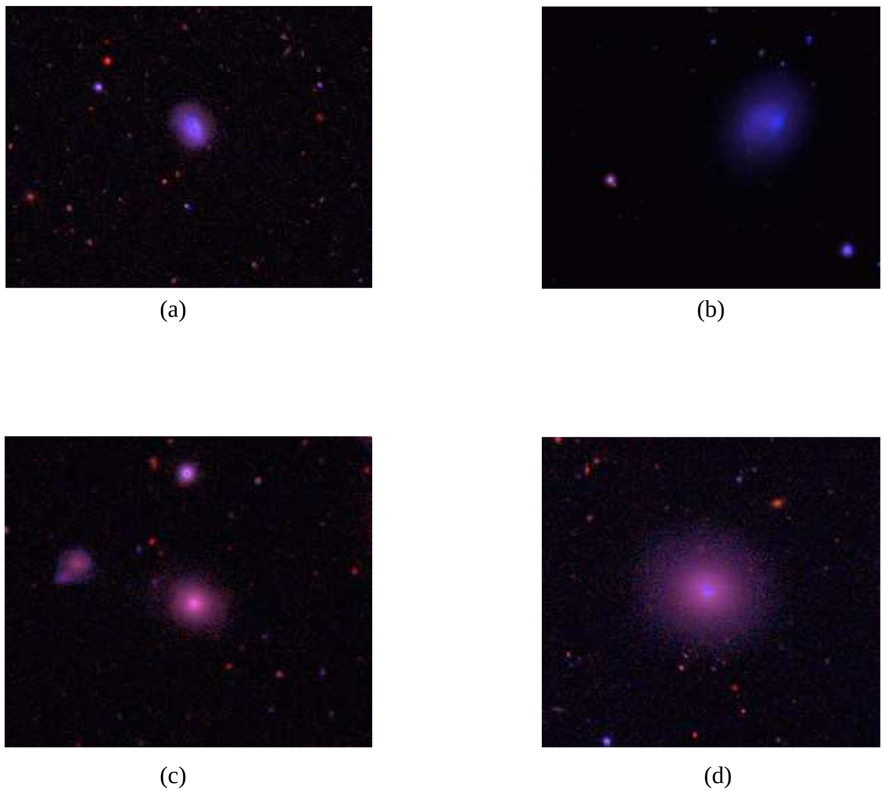

Fig. 2 The false-color RGB images of 4 starburst galaxies, which are obtained by using three (r, g, i) SDSS images with the method proposed by Lupton et al (2004). (a) A1212+06, $3'.5 \times 2'.5$; (b) A1216+04, $3'.2 \times 2'.5$; (c) CGCG 13-83, $3'.5 \times 2'.8$; (d) IC 225, $3'.2 \times 2'.8$.

IRAF, for A1212+06 and CGCG 13-83, which are shown in Fig. 4. The SDSS magnitude system (Fukugita et al. 1996) is quite similar to the AB system(Oke & Gunn 1983). The zero point of magnitude for each frame is obtained directly from the image header. For A1216+04, we do not apply the photometric measurement since it is a late-type blue compact dwarf (BCD) galaxy (Gordon & Gottesman 1981; Hoffman et al. 1987). The best fits with the de Vaucouleurs $R^{1/4}$ are shown as solid lines, fitting results are summarized in Table 3. We find that the fitting is quite well, and the rms is typically less than 0.1.

In order to derive the g-r color distribution, we first check the PSF profiles of g- and r-band images and then smooth the g-band image by convolving a Gaussian kernel to match r-band PSF. In Figure 5 we show the g-r color distributions for A1212+06(left) and CGCG13-83(right). It is very interesting to note that two sources show different behaviors. For the case of A1212+06, the nucleus is exceptionally blue, and becomes much redder continuously outwards. While for CGCG13-83, the color distribution is nearly

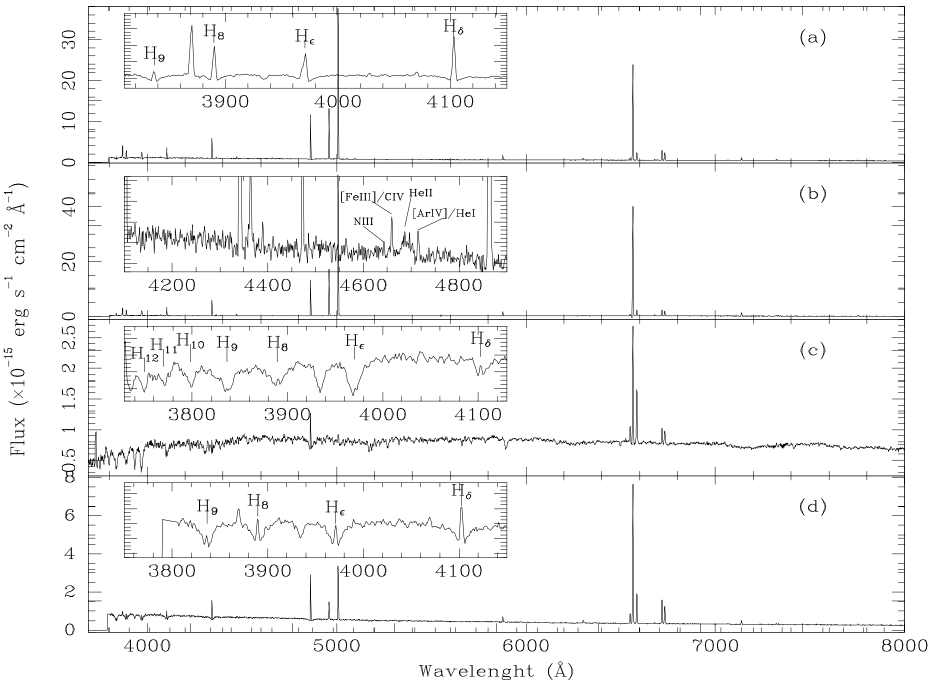

Fig. 3 The optical spectra of the starburst galaxies in our sample, taken from the Sloan Digital Sky Survey. The insets of (a), (c) and (d) show enlargement of the wavelength range of 3750 - 4150 Å, where the higher-order Balmer absorption lines are positively detected. The inset of (b) shows the magnified view of the W-R bumps around 4650 Å. (a) A1212+06; (b) A1216+04; (c) CGCG 13-83; (d) IC 225.

uniform, very similar to a compact elliptical galaxy IC 1639 (Wu et al. 2005) except for the inner ~5 arcseconds region. Our results indicate their modes of star forming activity might by different.

Table 3 The fitting results with de Vaucouleurs $R^{1/4}$ law for A1212+06 and CGCG 13-83.

	A1212+06			CGCG 13-83		
Band	μ_0 (mag arcsec^{-2})	r_e (arcsec)	rms	μ_0 (mag arcsec^{-2})	r_e (arcsec)	rms
g	7.6±0.3	0.83±0.06	0.07	13.6±0.1	5.2±0.3	0.06
r	8.8±0.4	1.2±0.1	0.09	13.1±0.1	5.3±0.3	0.07

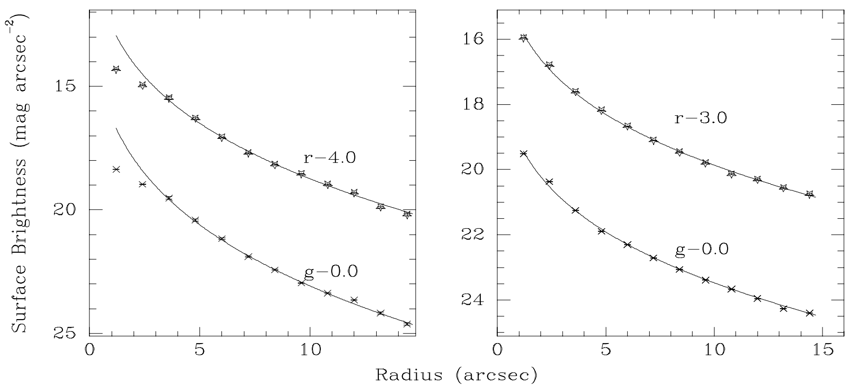

Fig. 4 The stellar surface brightness of 2-band (gr) SDSS images, the solid lines are the best fit with de Vaucouleurs $R^{1/4}$ law. The profiles are shifted for clarity. *Left panel:* A1212+06; *Right panel:* CGCG 13-83.

3.2 Star Forming Activity

3.2.1 A1212+06

A1212+06 is one member of the Virgo cluster and was identified as an HII galaxy by Maza et al. (1991) using the emission line ratios such as [O II]λ3727/[O III]λ5007, [N II]λ6584/Hα. Our stellar population synthesis fitting indicates that the monochromatic contribution at 4800Å from the young ($< 10^8$ yr), intermediate-aged ($10^8 <$ age $<10^9$ yr) and old ($> 10^9$ yr) stellar populations are 50%, 38% and 12%, respectively.

We use the standard method to compute the nebular extinction, based on the Balmer decrement and assuming Case B recombination and a standard reddening law (Cardelli, Clayton & Mathis 1989). For A1212+06, the observed $F_{H\alpha}/F_{H\beta}$ is 2.94, the nebular extinction, A_V, is estimated to be 0.076 mag. Thus the extinction-corrected Hα luminosity, $L^{corr}_{H\alpha}$, is 9.3 $\times 10^{39}$ $erg\ s^{-1}$. Using the empirical calibration given by Kennicutt (1998), SFR$_{H\alpha}$ is equal to 0.073 $M_\odot\ yr^{-1}$, note that the SFR$_{H\alpha}$ only accounts for the central 3 arcseconds region. At the same time, we could also estimate the SFR from the infrared (8-1000 μm) luminosity (Kennicutt 1998). The IR luminosity, L$_{8-1000\mu m}$, which is calculated by using the fluxes taken from the IRAS Faint Source Catalog (Moshir et al. 1989), is equal to 9.11×10^{42} $erg\ s^{-1}$ and the corresponding SFR$_{IR}$ is 0.41 $M_\odot\ yr^{-1}$,

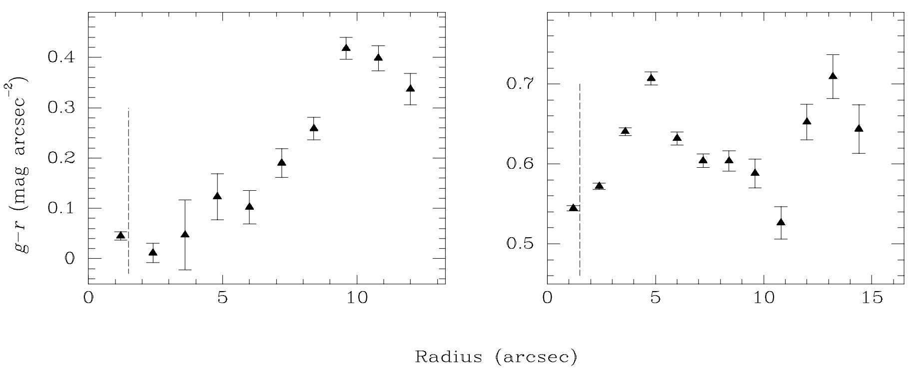

Fig. 5 The color (g-r) distributions for A1212+06 (left) and CGCG 13-83 (right). The vertical dashed line indicates the SDSS spectral fibre size.

much larger than SFR$_{H\alpha}$, which suggests that star-forming activity arises from larger area than the SDSS spectral fibre region, and also confirmed by the g-r color distribution.

3.2.2 A1216+04

Like A1212+06, A1216+04 is an HII galaxy in the Virgo cluster, too (Terlevich et al. 1991). Stellar population synthesis fitting indicates that a significant contribution from the young stellar components which contributes 86% of the total monochromatic flux at 4800Å. This fraction is much larger than the one (50%) in A1212+06. The observed $F_{H\alpha}/F_{H\beta}$ is equal to 4.38, the corresponding nebulae extinction is 1.17 mag, and SFR for the central 3 arcseconds region is 0.21 $M_{\odot}\ yr^{-1}$, it is very interesting to note that SFR deduced from IR emission is exactly the same as SFR$_{H\alpha}$, which indicates that the star-forming activity is very concentrated in the SDSS fibre covering region. In fact, this object is wrongly classified as an elliptical galaxy (Gordon & Gottesman 1981; Hoffman et al. 1987), and will omit from the further analysis.

The spectrum of A1216+04 shows the broad bumps at 4650 Å, as shown in the inset in Fig. 2b, which are characteristic of W-R stars (Conti 1991). The bump at 4650 Å contains stellar and nebular emission lines including He II λ4686, [Fe III] λ4658, N III $\lambda\lambda$4634-4641, [Ar IV] λ4711 and C IV λ4658. Thus we identify A1216+04 as a hitherto unknown Wolf-Rayet galaxy, however, the low S/N for the Wolf-Rayet features hampers us for further analysis.

3.2.3 CGCG 13-83

CGCG 13-83 has been regarded as an actively star-forming elliptical galaxy by Fukugita et al. (2004), who firstly found its strong Hα emission line. But the authors did not do any further analysis such as the stellar population synthesis and the radial profiles, which will be presented here. As shown in Fig. 3c, the spectrum for CGCG 13-83 clearly shows higher-order Balmer absorption lines in the wavelength range of $3750-4150$ Å, which have been taken as the unambiguous evidence of intermediate-aged ($\sim 10^8$ yr) stellar populations (Gonzalez Delgado, Leitherer & Heckman 1999; Gonzalez Delgado, Heckman & Leitherer 2001). Our stellar population synthesis modeling confirms that 46% of the monochromatic flux at 4800Å is due to the intermediate-aged ($10^8 <$ age $< 10^9$ yr) stellar components.

The observed $F_{H\alpha}/F_{H\beta}$ is equal to 4.25, the corresponding nebulae extinction is 1.09 mag, and SFR for the central 3 arcseconds region is 0.07 $M_\odot\ yr^{-1}$. All results are summarized as in Table 4.

Unlike A1212+06 and A1216+04, the [O III]$\lambda\lambda$4959, 5007 in CGCG 13-83 is rather weak and it can only be detectable after subtracting the best matched model from the observed spectrum. However, the radial profiles can be fitted with the R$^{1/4}$ law very well for g- and r-band images, as shown in the right panel in Fig. 4.

Table 4 The extinction for the nebular, the extinction-corrected H$_\alpha$ luminosity and the star formation rate of the three star-forming galaxies

Name	$A_V^{nebular}$ (mag)	$L_{\mathrm{H}\alpha}^{\mathrm{corr}}$ (erg s^{-1})	SFR (H_α) ($M_\odot$ yr^{-1})	L_{FIR} (erg s^{-1})	SFR (FIR) ($M_\odot$ yr^{-1})
A1212+06	0.076	9.30×10^{39}	0.073	9.11×10^{42}	0.41
A1216+04	1.17	2.71×10^{40}	0.21	4.60×10^{42}	0.21
CGCG 13-83	1.09	8.83×10^{39}	0.070	...	...

4 DISCUSSION

By using images and spectra from the SDSS, we have investigated the emission line properties for a sample of 11 elliptical galaxies with emission lines picked out from 48 ellipticals by cross-correlating the SDSS DR2 with RC3 catalog. We classify four HII galaxies, one of which (A1216+04) is in fact a late-type BCD and a new Wolf-Rayet galaxy, two (A1212+06 and IC 225) are dwarf ellipticals, and one (CGCG13-83) is an ordinary elliptical. Recently Guzman et al. (2003) and Graham (2005) find that dwarf ellipticals form a continuous extension, both chemically and dynamically, with the more luminous (ordinary) ellipticals. If we simply regard A1212+06 and IC 225 as normal

ellipticals, for our sample, the frequency of star-forming ellipticals is $3/47 = 6.38\%$, significantly higher than the value $2/210 \approx 1\%$ by Fukugita et al. (2004), which is probably caused by our selection criteria, small sample size and problems of morphological classification in RC3 (de Souza, Gadotti & dos Anjos 2004).

It is well known that bar, galaxy-galaxy interaction and merger are efficient mechanisms to trigger starburst activities for spiral galaxies (Huang et al. 1996; Zou et al. 1995). Since the star-forming elliptical galaxies are rather rare, the most possible mechanism for triggering starburst in the elliptical galaxies is still an open question. The most promising mechanisms to trigger the nuclear starbursts in the elliptical galaxies include interaction, major mergers and minor mergers (accretion events with the satellite less than 10% of the galaxy's mass) as suggested by Worthey (1997). Major mergers are the mergers of two disc galaxies of comparable mass, using the numerical simulations, Mihos & Hernquist (1996) have shown that starburst activities during the merger process could be two orders of magnitude higher than that in isolated galaxies and can be sustained from several 10^7 yr to $\sim 2 \times 10^8$ yr after the collision. It could be the case of many infrared luminous galaxies, which are found to show morphological peculiarities indicative of encounters, such as multiple nuclei, tidal tails, loops, and shells (Sanders et al. 1988; Sanders 1992). Though major mergers trigger the most powerful starburst, they are less common than minor mergers with the satellite less than 10% of the galaxy's mass. Ostriker & Tremaine (1975) and Tremaine (1981) have shown that for the typical galaxy, no matter of morphological type, several tens of percents of its mass has probably been accreted in the form of discrete subunits. And the numerical simulation of minor mergers between gas-rich disk galaxies and less massive dwarf galaxies are shown by Hernquist & Mihos (1995).

For CGCG 13-83, the light distribution is very smooth, there is no any sign of interacting remnant, such as tidal tails. However, when we search in the view field of 30 arcminutes by using the NASA/IPAC Extragalactic Database (NED), we detect two galaxies that possibly interact with CGCG 13-83. One is CGCG 13-84 (RA: 12h08m31.3s, Dec: +00d08m11s; z: 0.034942), which is about 2.5 arcminutes northeast to CGCG 13-83 and 15.2 mag (g-band). The other is SDSS J120828.48+000948.7 (RA: 12h08m28.490s, Dec: +00d09m48.90s; z: 0.03539), which is about 3.4 arcminutes northwest to CGCG 13-83 and 17.3 mag (g-band). Therefore, CGCG 13-84 is a most probably physical companion to CGCG13-83 according to the criteria proposed by Schmitt (2001). Meanwhile, previous numerical simulations indicate that gas inflows occur within a dynamical timescale (a few $\times\ 10^8$ yr) of the initial collision (Barnes & Hernquist 1991; Mihos et al. 1992, 1993), both suggest that the triggering mechanism for star forming activity in CGCG 13-83 is due to the interaction with CGCG 13-84.

For the case of A1212+06, the morphology is also very smooth. However, when we inspect the central region carefully, we find two distinct cores, which are clearly shown

in its RGB image. Due to the no-spatial information of SDSS spectrum, now we can't study the nature for both cores. For this object, long-slit optical spectroscopy is under consideration.

5 CONCLUSIONS

In this paper, we study a sample of 11 elliptical galaxies with emission lines. After removing old stellar contribution and using the standard classification criteria, we identify them into one Seyfert 2, six LINERs and four HII galaxies. For four HII galaxies, we find that one (A1216+04) is a new Wolf-Rayet galaxy, two ellipticals (A1212+06, IC 225) have two distinct nucleus, and CGCG 13-83 is possibly interacting with CGCG 13-84. We propose that the star-forming activities in elliptical galaxies could be triggered by either galaxy-galaxy interaction or the merging of a small satellite/a massive star cluster.

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